

Satellite-Connected IoT for Remote Connectivity

Kunal Singh

Professor

Department of Information Technology

Gayatri College of Engineering and Management

Email id: singhkunal40@rediffmail.com

ABSTRACT

This paper discusses the emerging field of satellite-connected Internet of Things (IoT) technology, which aims to deliver connectivity to devices in remote and unserved regions of the world. As terrestrial networks still do not cover many rural, maritime, or wilderness areas, satellite IoT offers a promising alternative by combining low Earth orbit (LEO), medium Earth orbit (MEO), and geostationary orbit (GEO) satellites with IoT networks. The review explores architecture, enabling technologies, major use cases, challenges, and future prospects of satellite IoT. Also, performance constraints, power usage, and cost implications are examined with specific examples. This work concludes that satellite IoT, while facing technical and economic barriers, is becoming indispensable in bridging the global connectivity gap especially for critical monitoring and remote sensing applications.

KEYWORDS: *Satellite IoT, Remote Connectivity, LEO, LPWAN, Maritime IoT, Agriculture Monitoring, Wireless Networks*

INTRODUCTION

In the recent decade, Internet of Things (IoT) has transformed how devices connect, communicate, and share data. Traditionally, IoT relies on cellular networks, Wi-Fi, or other terrestrial connections such as LoRa, Sigfox, and NB-IoT. But many geographical areas around the world are still without reliable terrestrial coverage because of rough terrain, low population density, or economic challenges. Satellite-connected IoT emerges as a vital solution for such areas, enabling communication directly through satellites. This paper provides a review of

current developments in satellite IoT linking, evaluating its architectural models, applications, limitations, and future trends.

BACKGROUND AND MOTIVATION

Satellite-connected IoT is a rapidly emerging paradigm that extends the capabilities of conventional IoT networks to regions where terrestrial connectivity is weak or unavailable. By leveraging satellites as communication relays, IoT systems can now operate globally, ensuring reliable and timely data transmission in environments previously considered unreachable.

1. What is Satellite IoT?

Satellite IoT refers to the integration of Internet of Things (IoT) devices with space-based communication infrastructure, enabling devices to transmit and receive data through satellites rather than relying solely on terrestrial networks such as cellular towers or Wi-Fi. In a typical satellite IoT ecosystem:

- a) **IoT Devices and Sensors:** These are deployed in remote or hard-to-reach locations. They monitor environmental parameters (e.g., temperature, humidity), track assets, or measure critical industrial metrics.
- b) **Satellite Communication:** Devices communicate directly or indirectly (through gateway nodes) with satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), or Geostationary Orbit (GEO). The satellites act as intermediaries, receiving signals from ground devices and forwarding them to ground stations.
- c) **Ground Stations:** These stations receive data from satellites and transfer it to backend systems. Ground stations may also handle command uplinks, sending instructions back to IoT devices.
- d) **Cloud or Edge Platforms:** Once the data reaches terrestrial infrastructure, it is processed, analyzed, and stored in cloud platforms. Edge computing may also be used for preliminary data aggregation or decision-making close to the data source, reducing the amount of information that needs to be transmitted.

Example Applications:

- Environmental monitoring in polar regions where no cellular coverage exists.
- Asset tracking in global shipping routes and oil rigs.
- Agricultural monitoring in sparsely populated rural areas.

In essence, satellite IoT eliminates the dependency on ground-based network infrastructure, offering **ubiquitous connectivity** for devices spread across geographically diverse or inaccessible regions. This capability is especially crucial for applications requiring real-time monitoring, predictive analytics, or automated responses.

2. Why We Need Satellite IoT

Despite the rapid expansion of cellular networks and terrestrial LPWANs (e.g., LoRa, Sigfox, NB-IoT), a significant portion of the Earth's surface remains poorly connected. Satellite IoT is essential for bridging this digital divide. Key motivations include:

a) Remote and Rugged Terrains:

- Mountain ranges, deep forests, and remote rural villages often lack the infrastructure needed for terrestrial IoT.
- Example: Monitoring landslide-prone areas or forest fire detection in mountainous regions requires sensors that can communicate reliably over long distances without cellular towers.

b) Maritime and Oceanic Applications:

- Oceans and seas cover over 70% of the planet, yet vessels, buoys, and offshore platforms frequently remain out of terrestrial network reach.
- Satellite IoT enables ship tracking, cargo monitoring, marine environmental sensing, and fishing fleet management.

c) Deserts and Sparsely Populated Areas:

- Remote deserts and semi-arid regions often have sparse populations, making traditional network deployment economically unfeasible.
- Example: Solar farms in the Sahara or remote wind energy installations rely on satellite IoT for operational data transmission.

d) Disaster and Emergency Response:

- Natural disasters such as earthquakes, floods, or hurricanes can destroy terrestrial infrastructure.
- Satellite IoT provides emergency connectivity for rescue operations, early warning systems, and critical infrastructure monitoring.

- Example: After an earthquake, satellite-enabled sensors can continue reporting gas leaks or structural damages even if cellular networks are down.

e) Industrial Automation in Remote Sites:

- Oil and gas fields, mining sites, and large-scale renewable energy installations are often located far from population centers.
- Satellite IoT ensures continuous monitoring and control of equipment, reducing operational risks and downtime.

f) Global Data Coverage and Sustainability:

- Satellite IoT enables collection of environmental and climate data globally, facilitating research, early warning systems, and smart agriculture.
- Example: Tracking glacier melting or ocean temperature variations requires sensors in inaccessible regions.

SATELLITE ORBITS AND CONNECTIVITY MODELS

Satellite IoT relies heavily on the type of orbit the satellite occupies, as orbit altitude, speed, and coverage determine latency, throughput, and connectivity reliability. Satellites are typically categorized into **Geostationary Orbit (GEO)**, **Medium Earth Orbit (MEO)**, and **Low Earth Orbit (LEO)**, each with unique characteristics suitable for different IoT applications.

1. Geostationary Orbit (GEO)

Overview:

- GEO satellites orbit at approximately **35,786 km** above the Earth's equator.
- They travel at the same rotational speed as the Earth, which makes them **appear stationary** relative to a fixed point on the ground.

Advantages for Satellite IoT:

- **Wide Coverage:** A single GEO satellite can cover nearly one-third of the Earth's surface. This makes GEO ideal for large-area broadcasts, maritime connectivity, and regional IoT deployments.
- **Simpler Ground Equipment:** Since GEO satellites are fixed relative to the Earth, IoT

devices can use stationary antennas without complex tracking systems.

- **Stable Links:** Continuous line-of-sight connection to the same satellite simplifies network management.

Limitations:

- **High Latency:** Due to the high altitude, round-trip signal time is around **500–600 ms**, making GEO unsuitable for real-time IoT applications like autonomous drones or robotics.
- **Signal Attenuation:** Long distance causes higher path loss; devices require stronger transmit power.
- **Cost and Launch Complexity:** Launching GEO satellites is expensive, and replacement cycles are long (~15 years).

Example Use Cases:

- Weather monitoring satellites providing continuous telemetry data to remote stations.
- Broadcasting firmware updates to IoT devices across a large country or continent.

2. Medium Earth Orbit (MEO)

Overview:

- MEO satellites orbit between **8,000 km and 20,000 km**.
- They travel faster than GEO satellites and do not remain stationary relative to a point on Earth.

Advantages for Satellite IoT:

- **Moderate Latency:** Round-trip latency is lower than GEO (~150–250 ms), which is acceptable for many IoT telemetry and monitoring applications.
- **Good Coverage:** Each MEO satellite covers a larger area than LEO satellites but smaller than GEO, requiring fewer satellites than LEO constellations for global coverage.
- **Navigation Integration:** Commonly used for global navigation satellite systems (GNSS), enabling IoT devices to access precise positioning and timing.

Limitations:

- **Moving Footprint:** Ground stations and IoT devices must track the satellite or use constellations to ensure continuous coverage.

- **Medium Cost:** Cheaper than GEO but more expensive than deploying LEO constellations.

Example Use Cases:

- GNSS-based IoT applications like precision agriculture, fleet tracking, and maritime navigation.
- Environmental monitoring where moderate latency is acceptable.

3. Low Earth Orbit (LEO)

Overview:

- LEO satellites orbit **between 500 km and 2,000 km** above Earth.
- They move quickly relative to the ground, completing an orbit roughly every 90–120 minutes.

Advantages for Satellite IoT:

- **Low Latency:** Round-trip delay is typically **20–50 ms**, suitable for near real-time IoT applications such as autonomous drones, industrial automation, and remote healthcare monitoring.
- **High Throughput:** Being closer to Earth allows higher signal strength and more efficient data transmission.
- **Scalability:** LEO constellations (like Starlink, OneWeb) can provide global coverage through a network of multiple satellites.
- **Cost Efficiency for Devices:** Lower link power requirements reduce the energy consumption of IoT devices.

Limitations:

- **Smaller Coverage per Satellite:** Each satellite covers a limited area, requiring **hundreds or thousands** of satellites for continuous global service.
- **Complex Ground Systems:** IoT devices may need antennas capable of tracking satellites, or data must be routed through ground gateways.
- **Short Satellite Lifespan:** Typically 5–7 years, requiring frequent replenishment.

Example Use Cases:

- Real-time monitoring of shipping fleets and cargo containers.

- Remote healthcare devices transmitting patient data in isolated regions.
- Smart agriculture and wildlife tracking requiring frequent data updates.

Table 1: Characteristics of Satellite Orbits

Orbit Type	Altitude (km)	Latency	Coverage	Typical Use
GEO	~36,000	High	Very High	Broadcast/TV
MEO	8,000–20,000	Medium	High	Navigation/IoT
LEO	500–2,000	Low	Moderate	Real-time IoT

ENABLING TECHNOLOGIES

Satellite IoT success builds on multiple technical areas:

1. Low Power Wide Area Networks (LPWAN)

LPWAN protocols such as LoRa and NB-IoT are adapted for satellite links for battery-efficient data transfer. LPWAN allows devices to send small amounts of data over long distances with low power.

2. Antenna and Modem Technologies

Satellite IoT devices often use specialized antennas and modems to communicate with satellites. Adaptive antennas that can adjust their direction and signal strength improve reliability.

3. Edge Computing Integration

Edge computing near remote nodes can filter and preprocess data so that only essential information travels over expensive satellite links, reducing cost and latency.

4. Cloud Backends and Data Platforms

Cloud platforms receive and process satellite IoT data, providing analytics, dashboards, and integration with applications.

DEPLOYMENT ARCHITECTURES

There are two main architectural models for satellite IoT:

1. Direct Satellite Connectivity

Devices with onboard satellite modems transmit directly to satellite without intermediate terrestrial infrastructure.



Figure 1: Direct Satellite IoT Communication

2. Hybrid Model

A hybrid model uses terrestrial networks where available and switches to satellite only when necessary. This saves power and cost.

USE CASES OF SATELLITE IOT

Satellite IoT is becoming instrumental in various sectors.

1. Agriculture and Environmental Monitoring

Remote farms and forests use sensors to monitor soil moisture, crop health, weather conditions, and water usage. Satellite IoT ensures connectivity where cellular is absent.

2. Maritime and Shipping

Ships and buoys in oceans can send location, weather, and engine data. This reduces maritime accidents, improves navigation, and supports fisheries.

3. Oil, Gas and Mining Sites

Remote extraction sites rely on automated monitoring of pipelines, equipment health, leak detection and energy usage.

4. Emergency and Disaster Response

In disasters like earthquakes or floods, terrestrial networks may fail. Satellite IoT ensures that rescue teams get real-time data and location information.

5. Wildlife Tracking and Conservation

Scientists track animal movements using GPS tags that send data through satellites. This helps in studying migration and protecting endangered species.

TECHNICAL CHALLENGES

Despite promising benefits, satellite IoT faces several challenges.

1. Power Consumption

Satellite communications require more power than terrestrial connections. IoT devices often run on batteries for long durations, so power optimization is crucial.

2. Latency and Throughput

Although LEO satellites reduce latency, they still cannot match fiber or 5G speeds. High data rate applications may be limited.

3. Cost Constraints

Satellite services are more expensive than typical cellular IoT. Cost of hardware, subscription, and launch can be high for small organizations.

4. Frequency and Spectrum Issues

Satellite IoT must carefully use radio spectrum to avoid interference. Regulatory approvals vary by country.

5. Network Scalability

As millions of IoT devices come online, satellite networks must scale. Managing bandwidth and data congestion becomes critical.

PERFORMANCE ANALYSIS

Performance measurement in satellite IoT is often focused on:

- **Latency** (Time taken for data to travel uplink and downlink)
- **Energy efficiency** (Power consumed per transmitted byte)
- **Reliability** (Packet delivery success rate)

Analytical tests show that LEO systems typically sustain **latency below 100 ms**, which is acceptable for many IoT use cases, while GEO systems often result in **latency above 600 ms**. These values vary with weather conditions, path loss, orbital position, and device capability.

CASE STUDY: AGRICULTURAL REMOTE MONITORING

In a pilot project in rural hills of a developing region, soil sensors were connected to LEO satellites. Data on moisture, nutrients and temperature helped farmers decide irrigation and fertilization schedules.

Table 2: Field Sensor Data Summary

Parameters Measured	Frequency	Data Size per Report
Soil Moisture (%)	Every 6 hr	50 bytes
Temperature (°C)	Every 3 hr	20 bytes
Nutrient Levels	Once/day	70 bytes

Farmers reported significant improvement in yield and water savings. The project, however, highlighted a challenge — periodic data loss due to temporary satellite link blockage by terrain features.

FUTURE TRENDS

1. Enhanced LEO Constellations

Future satellites will have higher throughput and on-board processing, enabling faster and more reliable IoT gateways.

2. Integration with 5G

Satellite IoT will increasingly integrate with 5G networks, enabling seamless switching between terrestrial and satellite links.

3. AI-Based Network Management

AI can optimize satellite beamforming, scheduling, and resource allocation, improving network efficiency.

4. Energy Harvesting Devices

Work on solar and ambient energy harvesting can minimize reliance on batteries, enhancing device lifetime.

5. Standardization and Interoperability

Global standards will help multiple vendors and satellites interoperating, reducing fragmentation.

DISCUSSION

Satellite IoT is valuable for many remote applications, but it is not always an outright replacement for terrestrial IoT. In areas with reliable ground networks, hybrid solutions work more cost-effectively. Yet as satellite technology becomes cheaper and more sophisticated with mega constellations, its adoption will increase. The need for global connectivity, supported by

satellite IoT, is also aligned with United Nations Sustainable Development Goals (e.g., connecting communities and enhancing disaster response). Policy frameworks will play a big role in wider deployment.

We observe that satellite IoT often requires trade-offs — cost vs coverage, low power vs data rate, and ease of deployment vs regulatory compliance. Solutions must be tailored to the specific use case — for example, long-term environmental sensors need extremely low data rates and minimal power, while maritime safety systems need robust high availability.

CONCLUSION

Satellite-connected IoT represents a promising technological frontier for providing connectivity in remote regions where terrestrial networks are absent or unreliable. Through the use of GEO, MEO, and particularly LEO satellites, IoT devices can now operate globally with predictable dependability. Despite challenges such as cost, power constraints, and spectrum regulation, satellite IoT is advancing quickly — supported by industry investments, new architectures, and novel technologies. As an essential complement to terrestrial connectivity, satellite IoT has significant potential to support agriculture, maritime operations, environmental monitoring, disaster response, and more. Continued research, better design practices, and global cooperation will help address current limitations and make satellite IoT an integral part of future global connectivity ecosystems.

REFERENCES

1. Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for Smart Cities. *IEEE Internet of Things Journal*.
2. Mahmoud, R., Yousuf, T., Islam, S. R., & Mohamed, A. (2015). Internet of Things (IoT) Security: Current Status, Challenges and Prospective Measures. *IEEE 3rd International Conference on Future Internet of Things and Cloud*.
3. Maral, G., Bousquet, M. (2009). *Satellite Communications Systems: Systems, Techniques and Technology*. Wiley.
4. Karnouskos, S. (2017). The Internet of Things: A Review. *IEEE Communications Surveys & Tutorials*.
5. Raza, U., Kulkarni, P., & Sooriyabandara, M. (2017). Low Power Wide Area Networks: An Overview. *IEEE Communications Surveys & Tutorials*.

6. Evans, D. (2011). The Internet of Things: How the Next Evolution of the Internet is Changing Everything. *Cisco White Paper*.
7. Cheng, X., Yang, D., & Yu, F. R. (2020). Satellite IoT: Architecture, Technologies, and Challenges. *IEEE Wireless Communications*.
8. Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions. *Future Generation Computer Systems*.
9. Liou, J. C., & Johnson, N. L. (2009). *Risks in Space from Orbiting Debris*. *Science*.
10. Dinh, T. Q., Tang, J., La, Q. D., & Quek, T. Q. S. (2017). Offloading in Mobile Edge Computing: Task Allocation and Computational Frequency Scaling. *IEEE Transactions on Communications*.